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SIMULATION OF SPACECRAFT INTERACTION WITH A PARALLEL-STREAMING PLASMA

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ABSTRACT

An experimental study of the wakes produced by spacecraft moving in the ionosphere is reported. The work was done in an argon ion beam simulation facility which incorporated features enabling the production of a low background density of slow ions and an essentially parallel ion beam. The occurance of these features, and their effect on the simulation validity in previous work is briefly reviewed. Stable variation of the divergence of the beam was possible and results are given of wake studies for a range of body size and potential in both parallel and divergent beams.

INTRODUCTION

The interaction of a conducting body, such as a spacecraft with the ionospheric plasma is a problem of great importance when considering such aspects as the drag on the body, the use of probes, radio frequency transmissions, radar detection, the excitation of plasma waves etc.

There are three ways in which the interaction can be studied. The first is by in situ measurements in space, using instruments which are carried by a spacecraft. In general, this method has so far yielded data which are difficult to interpret, and it is complicated and costly. Because of the complex nature of the interaction phenomenon, however, the complete answer to the problem will probably come from a future mission performed in the ionospheric regions of interest, and not from the two other methods, which must be regarded as complementary studies.

The second method is to numerically solve, using computer techniques, the equations (Vlasov and Poisson) which are normally used to describe the spacecraft - plasma interaction. This method is reasonably well established, but there is some controversy as to the significance and validity of assumptions (both physical and mathematical) used in the various theories; results have not been independently verified in detail, and extensive computation is both costly and time consuming.

The third method is laboratory simulation in which a stationary model is placed in an ion stream moving at velocities representative of those found in the ionosphere. This method has been used extensively, but a review of the facilities used show that at least one of two effects limited the validity of the simulation. Either the background density of slow ions was a large percentage of the beam ions, or the ion streams were not generally parallel but diverged as they moved down the simulation chamber. The present work is mainly concerned with the correction of the latter defect in the simulation.

THE CAUSES OF BEAM DIVERGENCE

In the ionosphere below about 1200 km altitude the particle and vehicle velocities are such that the ion velocities, V_i are in general lower and the electron velocities, V_e, are in general higher than the spacecraft orbital velocity i.e.

$$V_i < V_s << V_e.$$

This flow condition is referred to as mesothermal. In the satellite frame of reference the ions are seen as impinging on the spacecraft at a velocity V_s, and as following straight, parallel trajectories with a small randomised component, V_i, superimposed. The ions can therefore be represented by a high velocity monoenergetic directed plasma stream and the electrons by a group of particles in equilibrium at the electron thermal temperature. This property suggests the use of ion beams directed past stationary models as a means of simulation.

However, it is found that in most plasma streams which have been accelerated in the laboratory a component of the ion velocity transverse to the streaming direction arises from the unequal deflection of the individual ions as they pass through the accelerator system.

The first estimate of the magnitude of this effect was made by Clayden and Hurdle (Ref.1) who considered the transverse motion of ions which pass through a series of parallel wires and are deflected unequally, the magnitude of the deflection depending upon the passage distance from a wire. From their analysis it was concluded that while the ion temperature in the axial direction was equivalent to 10^3- 10^4 ^oK, the values in the radial direction were nearer 5 x 10^4- 10^5 ^oK.

The problem was also considered by Hester and Sonin (Ref.2) again by studying the unequal deflection of the ions, who estimated an effective ion thermal speed as

$$\overline{C_i} = \frac{8RU}{3\pi Z}$$

where R = source radius, U = ion flow speed and Z = distance downstream at which $\overline{C_i}$ is being calculated. This represents an upper bound for the ion thermal speed but should give a good estimate when Z <<R, i.e. $\overline{C_i}$ << U

The importance of this directional distribution of the ions which leave the accelerator grid is because it is one of the two main factors that cause the ion stream to spread out with distance down the chamber. The other factor is the radial space-charge field, which is minimised with the provision of adequate space-charge neutralisation in the beam chamber.

The magnitude of the divergence in the beam caused by these effects is usually indicated by calculating the divergence angle of the stream, θ. For a parallel beam $\theta = o$. The common method of calculating θ is to determine the width of the number (or current) density profile of the beam at some constant fraction of its maximum value for a series of axial stations along the beam. These quantities can then be used to estimate the divergence angle and the degree of linearity in the ion trajectories.

THE EFFECTS OF SLOW BACKGROUND IONS

When an ion beam passes through a neutral gas then charge exchange processes occur, resulting in the fast moving beam ions giving their charge to the slow background neutral particles. The net result is the production of a beam of fast moving neutral atoms parallel to the main ion beam, and a background of slow moving ions. The fast neutrals should not influence the spacecraft/plasma interaction, because of the large mean free paths which the particles possess. However, the slow background ions have a much larger residence time in the beam chamber than the beam ions, and may perturb the electric field about the spacecraft and significantly influence the charged particle distributions.

The most important effect that these slow ions will have will be the partial filling of the ion-depleted regions in the wake behind a body, as the slow ions will not, in general, possess any preferred velocity vector. In addition the current collection due to ions which impinge upon the body will be much larger in the case where slow ions are present in appreciable numbers. Discrepancies of up to a factor of two between experiment and theory can be explained by assuming a slow ion component of only 1% (Ref.3).

The problem of charge exchange was again considered by Clayden and Hurdle (Ref.1), who showed that the slow ion population increased with both the ion flow speed and the neutral gas background pressure. The problem was also studied in detail by Sajben and Blumenthal (Ref.4), who derived expressions for a low estimate to the number of slow ions by using the hard sphere model to describe the collisions, and for a high estimate by assuming that the neutral atoms gained no momentum in a collision but lost an electron to ions passing within a certain distance.

REVIEW OF PREVIOUS SIMULATION FACILITIES

The situation in several ion beam facilities which have been used in the past for investigating the wake structure and the interaction problem is summarised in Table 1. The first column gives the facility location and references to its design and experimental work. The second column notes the background pressure

Table 1. Summary of Simulation Validity

FACILITY (References)	SLOW ION EFFECTS	BEAM DIVERGENCE EFFECTS
TRW-STL (5,6,7)	Pressure ~2×10^{-6} torr, any effects should be negligible, not specifically mentioned	$\theta \simeq 3 - 4^{o}$, good value
RARDE (1,8)	n_s/n_f~ 0.1, causing severe distortion of current collection results	Difficult to estimate due to lack of data, source-like
USSR (9,10)	pressure ~4×10^{-5}torr, probably a reasonable figure, not specifically mentioned	$\theta \simeq 9^{o}$, moderate divergence
Caltech (4)	(a) 25.4 mm diameter source, n_s/n_f ~ 1, severe distortion (b) 300 mm diameter source, n_s/n_f ~ 6, very poor value	(a) $\theta \simeq 17^{o}$, source-like, very divergent (b) "moderate divergence", probably essentially parallel
ESTEC (11,12)	Pressure ~$2\text{-}6\times10^{-4}$ torr, probably giving some distortion because of the large chamber used	$\theta \simeq 11\text{-}14^{o}$, moderate divergence
MIT (2,13,14)	n_s/n_f ~ 0.02, good value	$\theta \simeq 10^{o}$, moderate divergence
Marshall SFC (15,16)	Pressure ~5×10^{-6}torr, any effects should be negligible	$\theta \simeq 6^{o}$, good value
ONERA (17,18,19,20)	n_s/n_f~0.05-0.2, good to severe distortion	$\theta \simeq 11^{o}$, moderate divergence

or the ratio of slow ions to fast beam ions, n_s/n_f. The third column lists values of the divergence angle, θ . More details can be found in Ref.21.

No attempts have been made to study the effects of a magnetic field on a spacecraft wake in ion beam facilities, but any effects will probably be negligible at spacecraft altitudes. In addition most of the facilities have used "cold" ions because the effects of random ion thermal motion are difficult to simulate. The thermal motion has the effect of smoothing out the features found in the wake, and of causing more rapid filling. Hence, this simulation defect (from which the present facility also suffers) is important. Hester and Sonin (Ref.2) attempted a partial simulation but the results were only preliminary and caution was urged in interpretation because the velocity distribution was not Maxwellian. The most promising results have been given in the ONERA facility (Ref.19) where transverse temperatures of 10, 700 and 1900 ^{o}K were given by inserting a negatively biased mesh between the source and the model position (following the suggestion of Ref.6).

It can be seen from Table 1 that no facility has fully satisfied the criteria for a parallel, fast ion stream. The two which best meet the requirements are those of TRW-STL and Marshall SFC, which should have a negligible slow ion population at the working pressures used, and had divergence of about 3-6^{o}.

The next best facility was that at MIT, with good slow ion suppression but $\theta \simeq 10^{o}$. The wake studies carried out in this facility give the most comprehensive set of data so far reported, and it is important to check the effects of divergence because of the fundamental nature of the results. The ONERA facility, although appearing as good as the MIT facility on paper, was usually worse under typical conditions due to the high background densities of slow ions found, a result of using a larger simulation chamber.

Therefore the situation can be summarised as follows. A simulation facility is needed in which the slow ions have been adequately suppressed, and in which the effect of divergence in the ion stream flowing past the model may be investigated by controlling this divergence by focussing and beam shaping techniques.

THE CITY UNIVERSITY FACILITY

With the aim of investigating wake structures in parallel and divergent ion streams the apparatus originally used by Clayden and Hurdle (Ref.1) has been acquired and modified. Apart from minor changes in the structural design of the ion source itself and the instrumentation used, modifications were made to reduce the effects of beam divergence and background ions. The necessary modifications were suggested by work on electron-bombardment ion engines. The similarity between the designs of simulation facilities and these engines has been noted many times.

The original single extraction mesh (0.075 mm diameter wire

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spaced 0.175 mm) was replaced by a pair of matched grids (140 holes of 3 mm diameter, 55% open area, 1.5 mm spacing) in order to achieve easier focussing and control of the beam. Focussing is easier using grids rather than a mesh, but the voltages necessary to give the correct scaling of ion velocity in the beam are generally lower than optimum for good focussing. It was found that the voltages on the accelerator grid could be raised above that needed for velocity scaling and the ions, having been extracted, were then slowed down by a virtual decelerator plane in the plasma of the beam chamber. The plasma potential appeared quite sensitive to variations in accelerator and mesh potential (see below for discussion of mesh), and as the beam ion energy was essentially equal to the difference between the ion source plasma potential and the beam plasma potential, the velocity could be tailored within certain limits to correspond to the velocities typically found in the ionosphere.

The most important modification in the attempt to control the divergence, however, was the rewiring of the electrical circuits, as shown in Figure 1. The mesh which lines the beam chamber, providing an equipotential surface for the beam following extraction, was biased independently of the accelerator circuit in contrast to Ref.1. This meant that the backstreaming ratio

$$R = \frac{\text{net accelerating voltage}}{\text{total accelerating voltage}}$$

could be easily varied. In ion engines R must be less than about 0.9 to prevent electrons backstreaming from the beam into the engine, thus distorting the performance figures. In the present application this is not important and values of R greater than unity can be used.

The divergence of the beams, under various combinations of accelerator and mesh voltage, was measured by determining the half-width of the current-density profiles at some fixed fraction of the total current at several axial stations in the beam (usually 8-10 positions over some 150 mm). The results for 40eV and 100 eV argon beams are shown in Figure 2. These energies correspond to ion velocities of about 14 and 22 km/sec. Circular satellite velocities are about 7-8 km/sec for altitudes from 1200 km to 100 km. It can be seen from Figure 2 that the minimum divergence achieved is around one degree, and the ease of control of θ is evident. The minimum value of θ was found for values of R in the range 1.05 to 1.15 i.e. slight mesh over-voltages tending to "Force" the ions back into paths parallel to the beam axis.

Stable operation of the beam was achieved, with and without neutralisation, over the range of R indicated. As the neutraliser current was decreased the electron density in the beam remained essentially constant and the electron temperature rose steadily. The plasma potential also varied, indicating sheath re-arrangement in order to provide particles striking the walls of the chamber with sufficient energy to cause neutralisation by secondary electron emission. Operation without neutralisation, however, tended to produce more plasma noise and non-Maxwellian electron distributions in the discharge, and was avoided unless a large Debye length was required.

The ion density in the beam was found to be a linear function of the discharge current in the ion source, and the electron temperature was found to be essentially independent of the current. The density could be varied over a range of 10^{13}-10^{15} m^{-3}.

In an attempt to reduce the slow ion density in the beam modifications were made to lower the attainable base pressure of the system without gas flow to about $5x10^{-6}$torr, and to increase the propellant utilisation of the source. This term, a common parameter in ion engine studies, is the ratio of the extracted ion beam current to neutral mass flow rate into the source expressed in terms of an equivalent current. As higher utilisations are generally achieved in large diameter engines the extraction diameter was increased from 30 mm to 50 mm. The source was then run at the maximum extracted beam current which could be achieved at the relevant values of accelerating voltage and discharge current. This procedure was usually one of high discharge energy loss, which again is not important in the present context although it is of great concern in ion engine work. The aim of this modification is, of course, to reduce the neutral atom efflux through the acceleration plane and hence lower the background density in the beam and the probability of charge-exchange collisions.

The results of the slow-ion modicications are shown in Figure 3, where the ratio of the slow ions to the total ion density is shown as a function of pressure. The slow ion density can be measured in two ways (Ref.2), either by using to collect the ions a plate which can be shielded from direct impingement by the fast ions (as used in Ref.1 also), or by measuring the current to a probe in the region directly behind a model, where fast ions cannot penetrate. Both methods gave consistent results, and the data points in Figure 3 represent average values of n_s/n_t.

It can be seen that the value of n_s/n_t varies between about 0.02 to 0.07 over the operating pressure range of $7x10^{-5}$ to $3x10^{-4}$ torr. This is lower than the results of Clayden and Hurdle(Ref.1) and can be favourably compared with those of Hester and Sonin (Ref.2) which varied from 0.01 - 0.05. The requirement for an operating pressure an order of magnitude lower in the latter case arises from the larger size chamber in which the experiments were carried out (500 mm diameter and 1.2 m long, compared with 100 mm diameter and 0.5 long in the present case.)

Figure 4 shows the effect of the slow ion number density upon a radial profile at a constant axial distance downstream in the wake. This position is one in which a small peak is apparent in the centre of the ion-depleted region. At high pressure $7x10^{-4}$ torr) this peak is very prominent, but as the pressure is lowered the peak height decreases and the depleted region deepens, as a result of the decrease in the slow ion density. The shape of the wake remains essentially constant for pressures below about 10^{-4} torr, where the density of slow ions is about 3%, as shown in Figure 3.

DIVERGENCE EFFECTS IN NEAR WAKES

This section presents some results for the effects of stream divergence on the rear wake of a sphere which is moderately large with respect to the Debye length in the surrounding plasma i.e. the ratio of sphere radius to Debye length, $r_s/\lambda_D > 1$. A co-ordinate system which takes the centre of the body as its origin is used i.e. an axial distance $Z/r_s = 1.0$ represents the rear surface of the sphere, and is the nearest a probe can approach.

The wakes were mapped using spherical probes with a size much smaller than the body size to gain resolution. For a small negatively biased probe the ion current to the probe is proportional to the ion density and ion flow speed. As the flow speed was essentially constant in each wake a current profile at a fixed negative probe potential is equivalent to a number density profile (as noted in Ref.2).

Figure 5 shows the rear wake of a sphere with $r_s/\lambda_D = 4.5$ in a flow with a Mach number (based on the ion acoustic speed) $M = 6.5$, and a sphere potential $eV/kT_e = \phi_s = -2.35$. The results are traced directly from the recorder output and show the effects of the radial and axial non-uniformity of the ion stream. Wakes are shown in a 1^o (parallel) beam and a 10^o (divergent) beam. In both wakes common features can be seen. A region behind the body is depleted of ions, and the space-charge imbalance set up attracts ions which have passed the body into the wake to fill up this region. When the attracted ions fill the wake and reach the centreline a peak in ion density is found where the streams meet. These features are common in sphere wakes (e.g. Refs. 2, 16). However, a comparison of the parallel and divergent wakes also shows some differences. The wake filling occurs nearer the body in the parallel stream and the density peak develops earlier. Further downstream this peak is more sharply defined in the parallel case and can be seen at greater distances from the body.

The reasons for this can be visualised by considering the trajectories of the ions streaming past the body. The potential sheaths surrounding the body will be the same in each case, but the ions will possess a transverse component of velocity in the divergent stream. This will mean that fewer ions will be deflected into the wake by the body potential and the space-charge, and that those ions which are deflected will tend to cross the wake centreline further downstream.

Figure 6 shows the results for a sphere with $r_s/\lambda_D = 3.0$, $M = 5.4$ and $\phi_s = -3.8$, and for divergence angles of 1^o, 10^o and 20^o. These two latter values are representative of the range of divergence angles generally found in previous work (see Table 1). Compared to the parallel case it can be seen that again the features in the wake appear later and are weaker in the divergent streams. Also the same trend is observed when the 10^o and 20^o beams are compared.

The sharper focussing of the downstream ion density peak in Figure 6, compared with the results of Figure 5 (specifically for the parallel case where least distortion of the wake features occurs), is a result of both the larger negative body potential and the decrease of r_S/λ_D, both of which act to enhance the effect of ion attraction and focussing in the wake. The appearance of the density peak nearer the body is also a result of the stronger ion deflection caused by these changes.

CONCLUSIONS

Some preliminary results for wakes behind bodies in a plasma stream which simulates ionospheric satellite conditions have been presented. The facility combines the features of good slow ion suppression with an essentially parallel (1° divergence) ion stream, and thus fulfills simulation criteria more exactly than in previous work.

Near wake results for the case of a negatively biased sphere showed several differences between the features in parallel and divergent streams:

a) the filling of the ion depleted region of the wake directly behind the body, caused by potential focussing and space charge effects, occurs further downstream in a divergent wake, the exact distance depending upon the degree of divergence present.

b) ion density peaks formed on the centreline, due to the convergence of the ions attracted into the wake, are lower in number density, less sharply defined and decay into the ambient plasma sooner in a divergent wake.

The magnitude of these effects is dependent upon the divergence of the stream, i.e. the larger the divergence then the less rapid the wake filling and the more diffuse the density peaks.

Although the differences are not large relative to the overall scale of the wakes they are quite distinct and consistent in their behaviour, and previous results should be considered with this in mind. The divergence-related wake modifications do not influence the general physical picture of wake formation which is emerging (Refs.2,14) but should be taken into account in any attempt to give detailed agreement between actual space experiments or theoretical studies and laboratory simulations.

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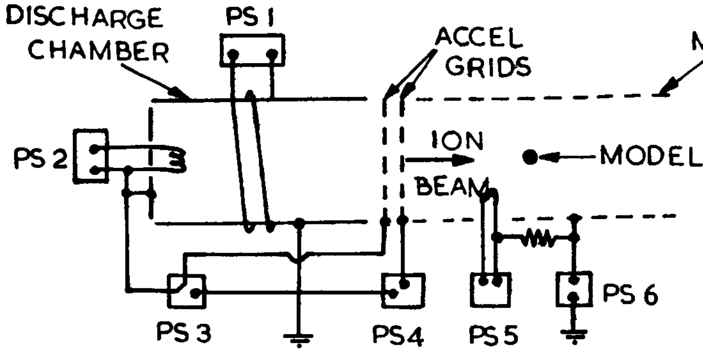

PS1 Magnetic field, 30V 10A
PS2 Filament supply, 12V 20A
PS3 Discharge voltage, 100V 2A
PS4 Accelerator supply, 350V 150mA
PS5 Neutraliser supply, 20V 10A
PS6 Mesh bias, 300V 2A

Figure 1--Wiring diagram for the parallel-streaming facility.

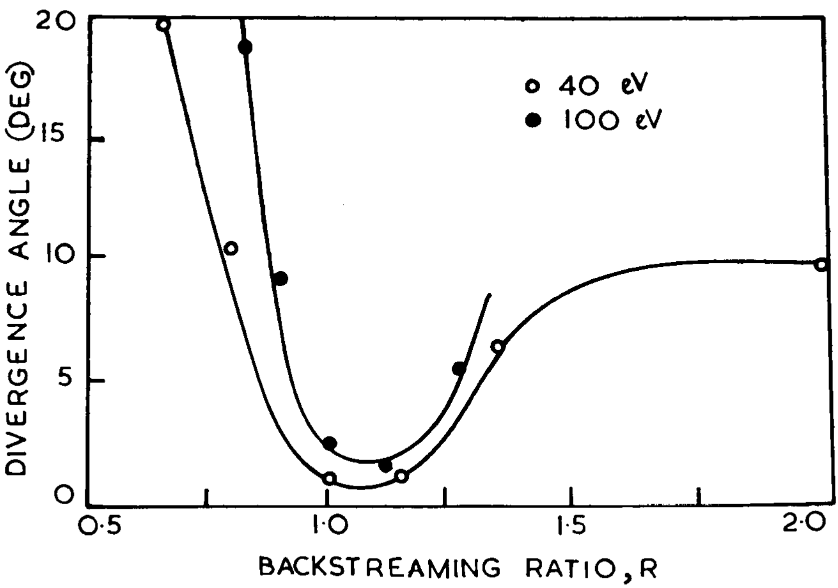

Figure 2--Divergence angle variation as a function of backstreaming ratio.

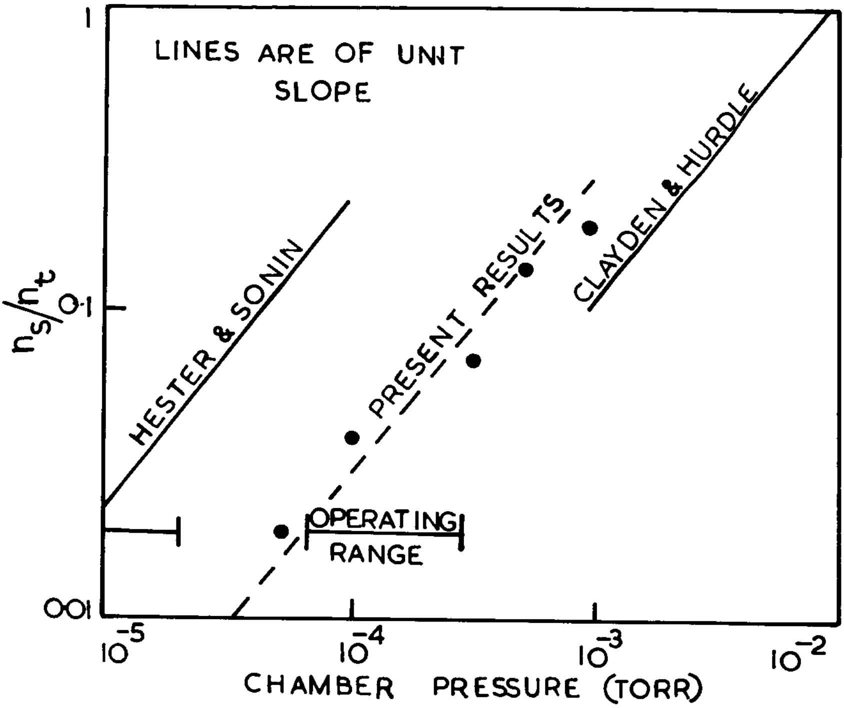

Figure 3--Variation of slow ion number density with chamber pressure.

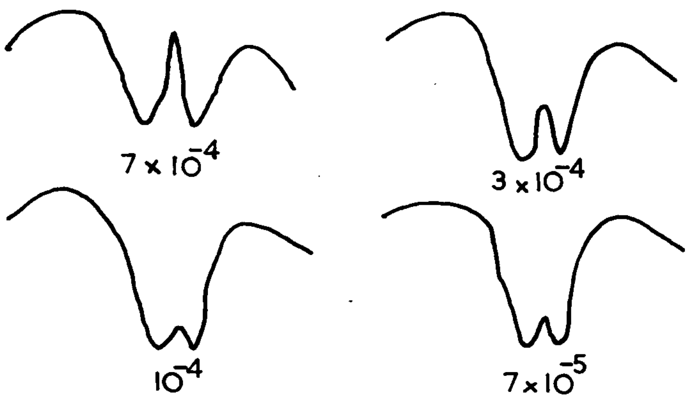

Figure 4--Effect of slow ion density on near wake shaping. (pressures in torr.)

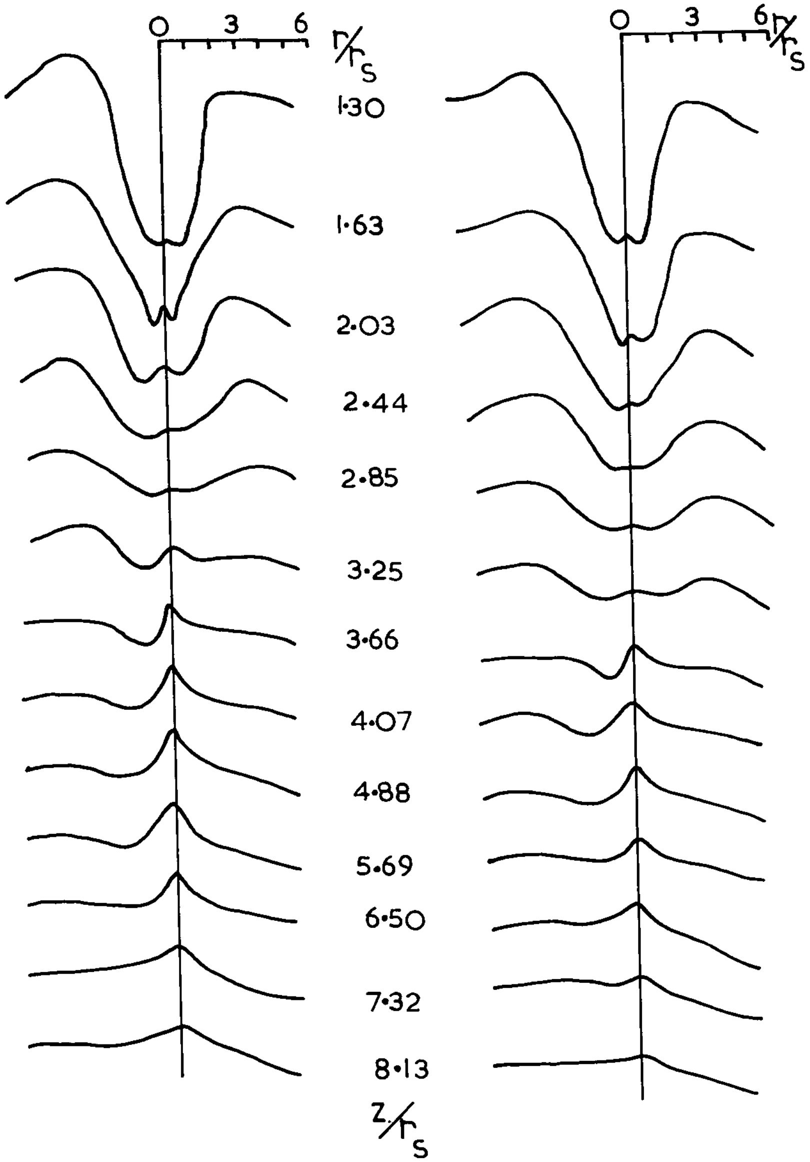

Figure 5--Near wake of a sphere $r_S/\lambda_D = 4.5$, $M = 6.5$, $\phi_S = -2.35$. Divergence $\theta = 1^\circ$ at left and 10° at right.

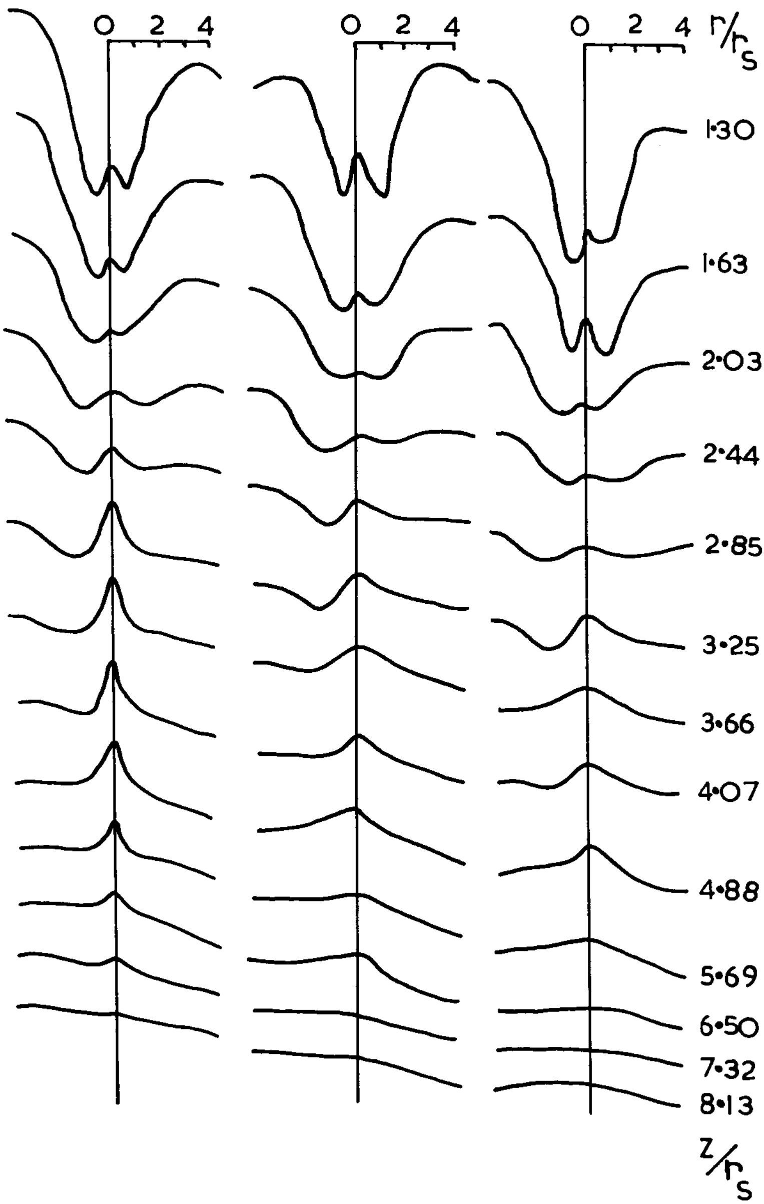

Figure 6--Near wake of a sphere $r_s/\lambda_D = 3.0$, $M = 5.4$, $\phi_s = -3.8$. Divergence $\theta = 1^\circ$ at left, 10° at centre and 20° at right.